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14. The boundary conditions imposed at depth and at the outer edge of the modeled region also affect the linearity of the problem. Constant potential temperature was imposed on both to model a deep geyser, while for a shallow geyser the outside edges were held at constant temperature but the bottom boundary was made insulating. The latter is an adequate approximation even if an H_2O-ice layer underlies the permeable layer, because the posited effective conductivity is roughly ten times that of ice.
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18. The distribution of temperatures under the actual collector will of course depart from the Neumann model as R_d increases. With constant flux, the model predicts decreasing temperatures toward the edges of the collector; in reality a decreased sub-greenhouse temperature leads to an increased downward heat flux. The actual temperature distribution will thus be intermediate between the Neumann and Dirichlet models, but the central temperature should be close to that predicted here. We have also calculated curves for a deep layer ($Z >> R_d$) but do not present them because viscous-relaxation calculations [R. L. Kirk, *Lunar Planet. Science* **21**, 635 (1990)] suggest that the global N_2 layer on Triton is no more than 30 to 100 m thick. A thick layer of high effective conductivity cannot be ruled out entirely, however, because the heat-pipe mechanism could operate in permeable H_2O-ice if the pore surfaces were encrusted with solid nitrogen. A further consideration is that the time required to warm a deep layer may exceed the length of the Tritonian summer. This is not necessarily a fatal objection, because condensation on the surface will prevent winter cooling from offsetting summer warming—provided gas flow cannot carry energy away from the subsurface layer—but localized eruption in the northern (winter) hemisphere would be as likely as eruption in the southern hemisphere in such a model. Curves for $Z_g = 1$ m are omitted here as well. They qualitatively resemble those for thicker greenhouse layers, but the limiting temperature is only about 42 K.
19. The power delivered to the geyser consists of insolation onto the source area (proportional to R_g^2) and the contribution from the collector (proportional to $R_g R_d$). The latter thus dominates for $R_g << R_d$, and because we find that $R_g \lesssim R_d/4$ is required for the peak temperatures of Eq. 6 to apply, we neglect the contribution of insolation onto the geyser.
20. The abrupt transition between $T = T_0$ on the geyser and $T = T_0 + \Delta T$ on the collector in the Dirichlet models leads to a $1/(R - R_g)$ divergence of the flux near the boundary, and hence a logarithmic dependence of P_{out} on the mesh spacing. In reality, the limit on available flux will lead to a temperature transition over a small but finite zone even if the inner edge of the greenhouse collector is perfectly sharp. The coefficients given in the text are for $R_g = 128$ mesh steps.
21. The calculation was carried out on a 5 by 257 mesh, with a mesh spacing of 20 m and R_g halfway between nodes at 75.5 steps from the axis. From the results for steady-state models, $R_g \simeq 1.5$ km implies $R_d \gtrsim 6$ km, and hence a collector operating near its maximum greenhouse temperature. We then find $Z_g \simeq 2$ m to achieve a temperature of 44.5 K.
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Temperature and Thermal Emissivity of the Surface of Neptune's Satellite Triton

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Analysis of the preliminary results from the Voyager mission to the Neptune system has provided the scientific community with several methods by which the temperature of Neptune's satellite Triton may be determined. If the 37.5 K surface temperature reported by several Voyager investigations is correct, then the photometry reported by the imaging experiment on Voyager requires that Triton's surface have a remarkably low emissivity. Such a low emissivity is not required in order to explain the photometry from the photopolarimeter experiment on Voyager. A low emissivity would be inconsistent with Triton having a rough surface at the ~100-μm scale as might be expected given the active renewal processes which appear to dominate Triton's surface.

SURFACE TEMPERATURE IS ONE OF several important factors that constrain models of the physical and chemical processes occurring on an object in the solar system. For this reason, several Voyager experiments endeavored to measure parameters from which the temperature of Triton could be determined. Triton's surface temperature has been derived or inferred by at least five separate Voyager investigations.

One technique is to develop a model atmospheric thermal profile and extrapolate it to Triton's surface. This method was employed by the investigators on the ultraviolet spectrometer (UVS) experiment (*1*). Their atmospheric model thermal profile, extrapolated to Triton's surface, was consistent with a surface pressure of 14 μbar. This is the equilibrium vapor pressure of nitrogen, a proposed dominant atmospheric gas, at 37.5 K. Likewise, the atmospheric occultation experiment conducted by the radio science (RSS) team investigators is consistent with the equilibrium atmosphere pressure derived by UVS if a model is fit which assumes an inversion layer in Triton's atmosphere at a height of 5 km above the surface (*2*).

A direct method of determining the temperature of Triton's surface is to measure the thermal radiation emitted at infrared wavelengths. The Voyager Infrared Interferometer Spectrometer and Radiometer (IRIS) measured the infrared radiation emitted from Triton's surface. The IRIS investigators averaged 16 infrared spectra from Triton's dayside and their best fit to the data yielded a temperature of 38 K, assuming that Triton radiates like a blackbody (for which emissivity = 1.0). They estimated the error in their measurement by deriving the temperatures expected by adding an additional 5% to the RMS residual of the fits. This is considered to be a conservative, subjective estimate of the 2 σ errors (*3*) and yields a temperature of 38^{+3}_{-4} K. They also fit a model to the IRIS data which assumed an emissivity of 0.5 which resulted in a temperature of 41^{+3}_{-5} K. This result is somewhat higher but has an error large enough to be consistent with the UVS result (*4*).

Photometric data have also been employed for determining Triton's surface temperature (*5*). This requires calculation of Triton's bolometric Bond albedo (the ratio of the integrated energy flux over all wavelengths from Triton in all directions to the solar insolation). Estimation of the bolometric Bond albedo permits derivation of an average temperature assuming thermal equilibrium.

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To measure the bolometric Bond albedo of Triton, its brightness must be measured at a wide range of solar phase angles so that a phase curve can be derived. Such a set of measurements can only be made with a deep space mission to the Neptune system, and Voyager provided the first measurements of Triton over a wide range of solar phase angle.

The Voyager spacecraft carried three instruments which could measure the reflected solar radiation from Triton's surface and produce a solar phase curve at discrete wavelengths throughout the region of the maximum of the solar emission. These were the Photopolarimeter (PPS) experiment, the Imaging system (ISS), and the radiometer channel of the IRIS experiment. The wavelength range accessible by the combined data set from the PPS and ISS experiments samples the wavelength range between 0.25 and 0.75 μm, about 70% of the whole solar energy output, at discrete filter wavelengths. Preliminary phase curves have been produced from both experiments and these have been presented in the literature. The radiometer results are currently being analyzed by the IRIS team.

The ISS results have been presented in two studies. Smith *et al.* (*6*) published preliminary results for the imaging system violet (0.41 μm) and green (0.56 μm) filters. Hillier *et al.* (*7*) reported a subsequent analysis of the violet and green ISS filters along with the results for the ISS blue filter (0.48 μm).

The PPS team has produced phase curves of Triton from the PPS ultraviolet (0.25 μm) and the infrared (0.75 μm) filters. These results have been combined with an independent PPS team reanalysis of the same ISS violet and green filter data reported by Smith *et al.* (*6*). These results were presented by Nelson *et al.* (*5*).

The phase curves presented in these analyses can be used to determine Triton's Bond albedo by calculating the geometric albedo and phase integral at each filter bandpass. The geometric albedo p_λ of a solar system object is defined as the brightness of the object when observed at 0 degrees phase angle at wavelength λ divided by the brightness of a perfectly diffusing disk at the same position (*8*). No Voyager observations were made at 0 degrees phase and therefore the phase curves are extrapolated to 0 degrees phase angle in order to make the determination (*5*). The phase integral of a solar system object is a measure of the angular scattering properties of the surface at a specific wavelength. Following Russell (*8*), it is defined as:

$$q_\lambda = 2\int_{\alpha=0}^{\pi} \Phi_\lambda(\alpha)d\alpha \qquad (1)$$

Table 1. Bond albedo as a function of wavelength.

	uv (0.25 μm)	v (0.41 μm)	b (0.48 μm)	g (0.56 μm)	ir (0.75 μm)
Smith *et al.* (*6*)		0.90		0.88	
Hillier *et al.* (*7*)		0.79	0.83	0.87	
Nelson *et al.* (*5*)	0.35	0.81		0.81	0.51

where $\Phi(\alpha)$ is the brightness at a phase angle α for radiation of wavelength λ. The Bond albedo is defined as $A_\lambda = p_\lambda q_\lambda$. The bolometric Bond albedo is the Bond albedo integrated over all wavelengths.

Nelson *et al.* (*5*) derived their v and g filter results from the same set of data that was used by Smith *et al.* (*6*) (Table 1). The difference between the two results is only due to the difference in technique used by the investigators to determine the geometric albedo and the phase integral. Nelson *et al.* (*5*) used the same technique for both the PPS and the ISS data. The significance is that the PPS reports a much lower Bond albedo at wavelengths shorter than and longer than the ISS results. This is not due to differences in the reduction techniques but to differences in the actual brightness reported by the two instruments. This difference serves as a measure of the true difference in absolute flux measured by two instruments which are independently calibrated, although variation of spectral absorption as a function of wavelength cannot be ruled out as the cause.

The results of these efforts to determine the Bond albedo as a function of wavelength can, and have, been used to estimate the bolometric Bond albedo for Triton. The bolometric Bond albedos are 0.90, 0.86, and 0.65 for the investigations of Smith *et al.* (*6*), Hillier *et al.* (*7*), and Nelson *et al.* (*5*), respectively.

The implications of an extremely high bolometric Bond albedo are shown in Fig. 1. The figure expresses the surface temperature as a function of emissivity for a range of bolometric Bond albedos ($0.65 < A < 0.90$). The temperature reported by the UVS investigation is shown as a horizontal line at 37.5 K. The results of the IRIS investigation for emissivities of 0.5 and 1.0 are shown as two points with vertical error bars. The Bond albedos reported by the ISS investigations are shown as broken lines and the bolometric Bond albedo reported by the PPS investigation is shown as a solid line. The curves are calculated from the expression:

$$T^4 = S(1 - A)/(4\epsilon\sigma) \qquad (2)$$

where T is temperature, S is the solar flux at Triton, A is Triton's bolometric Bond albedo, ϵ is Triton's emissivity, and σ is the Stefan-Boltzman constant.

Inspection of Fig. 1 indicates that the bolometric Bond albedo reported by Smith *et al.* (*6*) is not consistent with the IRIS results even for an emissivity <0.5. The results of Smith *et al.* (*6*) are only consistent with the 37.5 K basal surface temperature reported by UVS if the emissivity of Triton is ~0.35. Those of Hillier *et al.* (*7*) are

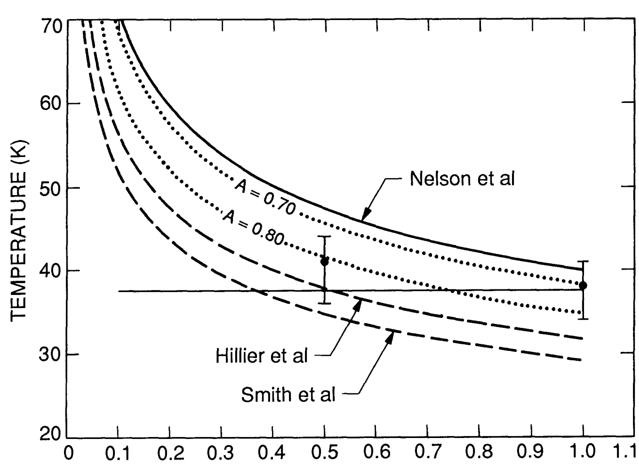

Fig. 1. Triton's surface temperature as a function of emissivity for a range of bolometric Bond albedos ($0.65 < A < 0.90$). The surface temperature reported by the UVS team is shown as a solid horizontal line at 37.5 K. The IRIS results for emissivity of 0.5 and 1.0 are shown as single points with vertical error bars. The ISS bolometric Bond albedos based on the data in Smith *et al.* (*6*) and Hillier *et al.* (*7*) are shown as broken lines. The bolometric Bond albedo reported by the Voyager Photopolarimeter (PPS) is shown as a solid curve. The dotted lines represent two curves for albedos 0.7 and 0.8 which are intended for use as a guide. The ISS results are only in agreement with Triton's 37.5 K temperature for emissivities that are lower than 0.5. The bolometric Bond albedo determined by PPS analysis is consistent with Triton behaving like a blackbody at 37.5 K.

consistent with the UVS and IRIS results only for emissivities of ~0.5, whereas the results of Nelson *et al.* (*5*), with the combined PPS and ISS data sets, are consistent with Triton being a blackbody (emissivity = 1).

It is commonly assumed that the emissivity of a material is related only to its spectral reflectance. At ultraviolet, visual, and near infrared wavelengths the spectral reflectance is determined by chemical composition. We note, however, that the wavelength of the peak of the thermal emission of a blackbody at Triton's 37.5 K surface temperature is ~80 μm. Most of Triton's thermal emission is longer than that wavelength. We suggest that even at these long wavelengths, the texture of the surface plays an important role in determining the emissivity.

The net heat flux from a surface depends on the emissivity of the surface material and the fourth power of the temperature. The apparent emissivity (and the brightness) of a surface are closely related to the geometric properties of the surface as well as the composition. It has long been recognized that the emissivity of a cavity radiator is essentially independent of the emissivity of the material from which the cavity is constructed. If the frost on Triton's surface has the geometric properties of a cavity radiator (depth of cell >> opening of cell; that is, similar to a honeycomb) then the emissivity of the surface will approach unity, without a strong relationship to the reflectance properties of the material from which the surface is composed.

It is strongly believed from other Voyager investigations that much of Triton's surface is freshly deposited. For example, Hansen and colleagues (*9*) have presented convincing evidence for rapid resurfacing of Triton as a result of currently active geyser-like processes. We would expect that the precipitated deposits would be loosely compacted and not smooth, resembling the "fairy castle" analogy often invoked in discussions of reflectance properties of candidate materials of planetary surfaces. This would be consistent with Triton having a rough surface at the >100-μm scale. The thermal energy emitted from such a surface at a wavelength of ~100 μm would closely approximate the radiation emitted from a blackbody which is inconsistent with the low emissivity required to explain the ISS data (*10*).

In order for Triton's emissivity to be consistent with the ISS photometry, two conditions need to be satisfied. First, the spectral reflectance of the ices which dominate Triton's surface must be very high (emissivity is low) at wavelengths ~80 μm and longer. Second, Triton's surface must be smooth at the ~100-μm scale.

An alternative explanation is that there may remain some uncertainties in the absolute calibration applied to the ISS results. If the ISS phase curves more closely approximated the PPS phase curves, then Triton's surface could easily be approximated by a blackbody.

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11. This work was performed at Jet Propulsion Laboratory under contract with NASA.

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Energy Sources for Triton's Geyser-Like Plumes

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Four geyser-like plumes were discovered near Triton's south pole in areas now in permanent sunlight. Because Triton's southern hemisphere is nearing a maximum summer solstice, insolation as a driver or a trigger for Triton's geyser-like plumes is an attractive hypothesis. Trapping of solar radiation in a translucent, low-conductivity surface layer (in a solid-state greenhouse), which is subsequently released in the form of latent heat of sublimation, could provide the required energy. Both the classical solid-state greenhouse consisting of exponentially absorbed insolation in a gray, translucent layer of solid nitrogen, and the "super" greenhouse consisting of a relatively transparent solid-nitrogen layer over an opaque, absorbing layer are plausible candidates. Geothermal heat may also play a part if assisted by the added energy input of seasonal cycles of insolation.

Several hypotheses regarding the energy sources of Triton's geyser-like plumes involve absorbed insolation or combinations of absorbed insolation and geothermal heat (*1*). Although it may seem unreasonable that a surface absorbing only 20% of the incident sunlight at 30 AU (*1, 2*) could manifest effects as dramatic as Triton's plumes, we will show that there are indeed ways to trap and store enough solar energy in Triton's surface such that it is quite conceivable that Triton's plumes are a direct result of the impending maximum summer solstice in Triton's southern hemisphere. We will not attempt to discuss the physical or thermophysical characteristics of the eruptions here, nor the mechanisms whereby fluids and gases are delivered to the volcanic vents; these subjects will be discussed in separate papers in this issue by Soderblom *et al.* (*3*) and Kirk *et al.* (*4*).

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It has been known for several years that Triton has frozen volatiles on its surface, the most spectrally dominant being methane and nitrogen (*5–7*). From ground-based observations made in the 2.0- to 2.5-μm spectral region, Cruikshank *et al.* (*7*) concluded that molecular nitrogen must be present over most of Triton's visible surface in a layer at least 50 to 100 cm thick to explain the depth of a 2.15-μm absorption band in Triton's spectrum. Lunine and Stevenson (*8*) correctly concluded that nitrogen on Triton was mostly solid rather than liquid as originally proposed by Cruikshank *et al.* (*7*). Voyager 2 found nitrogen to be the dominant constituent of Triton's atmosphere with trace amounts of methane also present (*9*). Triton's ~15-μbar surface pressure (*9, 10*) is consistent with the vapor pressure equilibrium of nitrogen gas over the solid at the 38 K global average temperature observed by the Voyager IRIS experiment (*11*). The basal atmospheric pressure on Triton is thus sufficient to buffer, via global